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R&D Program for PVC Material Properties and Bonding

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1. Introduction

The Totally Active Scintillator Design (TASD) relies on the use of PVC extrusions as the main structural support. This presents a problem because PVC extrusions are typically not used as structural members and there are no commonly used design references or design specifications that can be used as a guide when designing the TASD structure. As a result it is necessary to perform an R&D program on the PVC, the extrusion structures, and the method of bonding the extrusions together in order to have a thorough understanding of their properties to form the basis for designing the structure. The purpose of such an R&D program is threefold:

- To test PVC extrusions in order to compare their actual performance to the performance predicted by FEA analysis. This will give insight and confidence in the ability of FEA to model the behavior of the TASD structure.
- To investigate the properties of PVC and the effect of titanium dioxide on the strength and creep properties of the material.
- To investigate methods for bonding PVC. There are two critical bonding applications. The first is the method of bonding the bottom seal and the fiber manifold to the extrusion. The second is the method for bonding extrusions together to form the TASD structure.

Once the basic structure of the TASD design is understood there are several important next steps that must occur. First, a complete failure analysis of the structure needs to be conducted so that every possible mode of structural failure or instability has been addressed. Second, the design of the bookends and a determination of how many are required need to be addressed. Finally, the assembly methods for the structure need to be examined.

This paper describes a R&D plan to address all of the mechanical engineering issues associated with the TASD design. It is divided into the following sections

2.0 Physical Testing of Extrusions for FEA comparison
3.0 PVC properties
4.0 Epoxy Properties
5.0 “Half Scale” 4 Plane Prototype
6.0 Design and Analysis of TASD Structure and Extrusions - Future Work

2. Physical Testing of Extrusions for FEA Comparisons

FEA modeling has been used to gain an understanding of how PVC extrusions will perform in the TASD structure. Further FEA modeling will be done to understand the performance of the assembled TASD structure. This modeling will be used to gain insight into the basic geometry of the extrusions that is needed to minimize deflections and stresses. The thin members, high stresses, stress concentrations, and the use of plastic make modeling the TASD structure challenging for FEA. As a result it is important to be able to correlate the actual performance of PVC extrusions to the performance predicted by the FEA modeling. The FEA modeling to date has focused on the geometry of the TASD extrusions. Therefore, it is impossible to perform any physical testing to confirm the results of the FEA results.

At this time the only extrusions that are available for this comparison are commercial panels fabricated by ExtruTech in Manitowoc, WI. These panels consist of 34 cells that are 1" x 1 5/8" with 1/16" thick (side wall) and 1/32" (rib). These panels have 8% titanium dioxide by weight. The vendor believes that for this type of extrusion this is the optimum percentage for the extrusion process. Several 8ft long panels have are being used at ANL for physical testing and there are currently 27ft and 15ft long panels which will be used to construct a 4 plane prototype that is 27ft x 15 ft. Physical tests will be performed using these panels and compared to FEA models in order to evaluate the accuracy of these models. These panels can be seen in Figure 1 below.

Figure 1. Commercial Extrusions

The purpose of the testing of the commercial extrusions is to examine the ability of FEA to model the performance of the PVC extrusions and to address some of the following the critical questions regarding the PVC extrusions.

- First, will the bottom horizontal extrusion buckle when subjected to the load from the extrusions above?
- Second, will the interior web of the extrusion buckle when subjected to the compressive load?
- Third, can the extrusions withstand the pressure created in the vertical orientation? FEA models have been created in order to examine each of these questions. The following tests have been conducted to examine the accuracy of the FEA model with the actual extrusion performance.

2.1. Buckling of the Panel

If unrestrained laterally the horizontal extrusions will be subjected to a buckling load. The maximum buckling load will be applied to the bottom extrusion which would have to support the entire weight of the modules above it which corresponds to a load of approximately 52.7 lbs/in. along the length of the extrusion. In the extreme case in which the bottom extrusion would have to support the entire weight of the upper extrusions and would not have any lateral restraints a total load of 52.7 lbs/in. would have to be supported by the bottom extrusion.

Figure 2 below shows the test setup used to test the load at which a panel will buckle. Ten panels were tested. The test sample has a dimension 27” high by 24” long with 26 cells. The cell profile is 1” x 1 5/8” with 1/16” thick (side wall) and 1/32” (rib). Every panel buckled at 208 lbs. This corresponds to a load of 8.66 lbs/in or 5,971 lbs over the length of a 17.5m long horizontal extrusion. This indicates that a 17.5m long horizontal panel that is unrestrained on its sides could only support the weight of approximately 2 additional horizontal extrusions above it. (~2,135lbs per 17.5m long extrusion filled with liquid)

Ang Lee at FNAL created a FEA model of these panels. Three calculations were been done to compare with the experiment data. The first one was a 2-D buckling model by using a plane element. The second one was a 3-D model with a thin shell element. The third one was an analytic solution. The comparison is summarized in Table-1 below.

Table 1. Comparison between the Test Data and Calculation Result

	Experimental Data	FEA 2-D model	FEA 3-D model	Analytic Solution
Collapsing Load (lb)	208	199	193	180
Difference with test data (%)		5%	7%	17%

Figure 2. Test piece for a commercial PVC panel

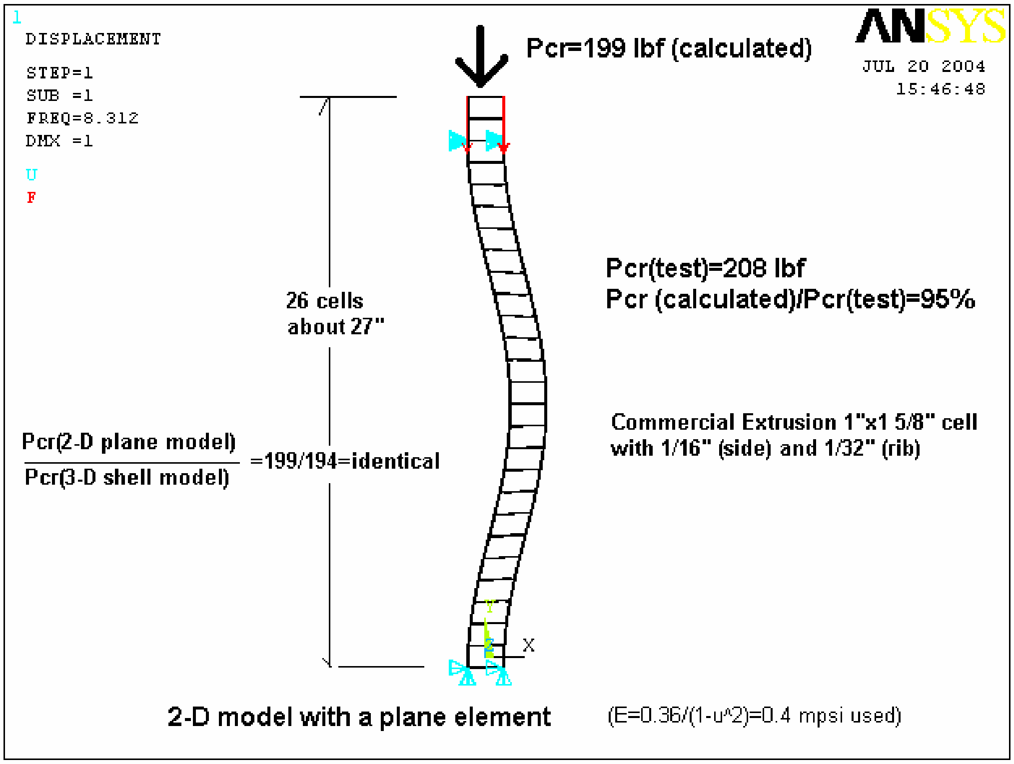

Figure 3. A 2-D finite element model with a plane element

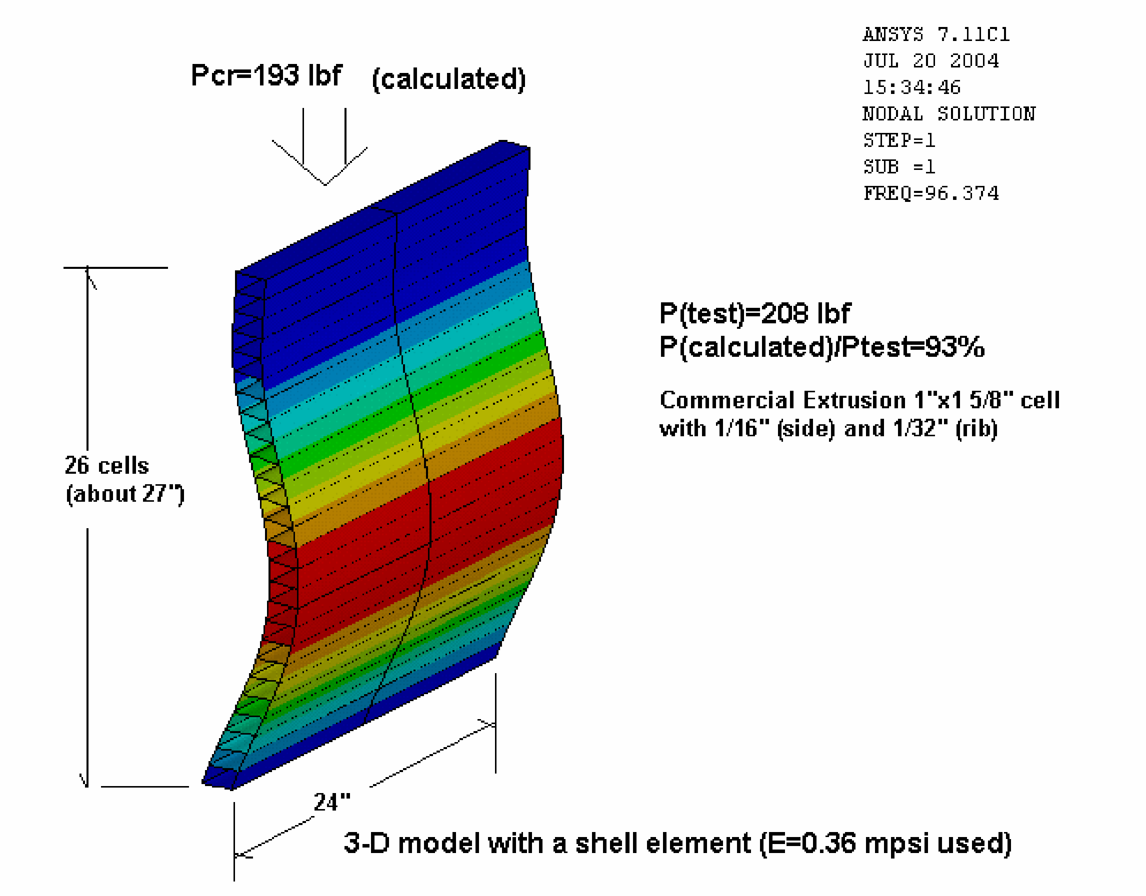

Figure 4. A 3-D FEA model with a thin shell element

2.2. Cell Buckling

Another failure mode is if a horizontal extrusion lost its liquid and the side walls had to support the entire load of the extrusions above it. For the bottom extrusion in this extreme case the full size horizontal extrusion would be loaded with 36,293 lbs. or 52.6 lbs/in.

Individual cells were also cut out of the commercial panels and compressed to failure. Figure 5 shows the test specimen in the Tinius Olson tensile/compression machine and Figure 6 shows an example of a buckled cell. A single 8" long cell was cut out of the commercial extrusion. This test simulates the condition where the cells in the horizontal extrusions lost its liquid and the side walls had to support the entire load. In the completed TASD structure the extrusion are restrained on the sides by adjacent extrusions, therefore if a single horizontal extrusion lost its liquid the side walls would have to support the entire load and would be subjected to buckling.

Figure 5. Test Setup for Buckling Test on Individual Cells

A total of 20 samples were tested with an average load to buckle of the side wall of 2122 lbs and a standard deviation of 583.6 lbs. For the 8” long sample this corresponds to 265 lbs/in. For the full size horizontal extrusion then the load capacity of the extrusion would be 182,751 lbs. For the bottom horizontal extrusion then this load is 5 times greater than the weight of all of the extrusions loaded above it. Therefore, if the extrusions are restrained for lateral motion then the bottom horizontal extrusion can easily support the weight of extrusions above.

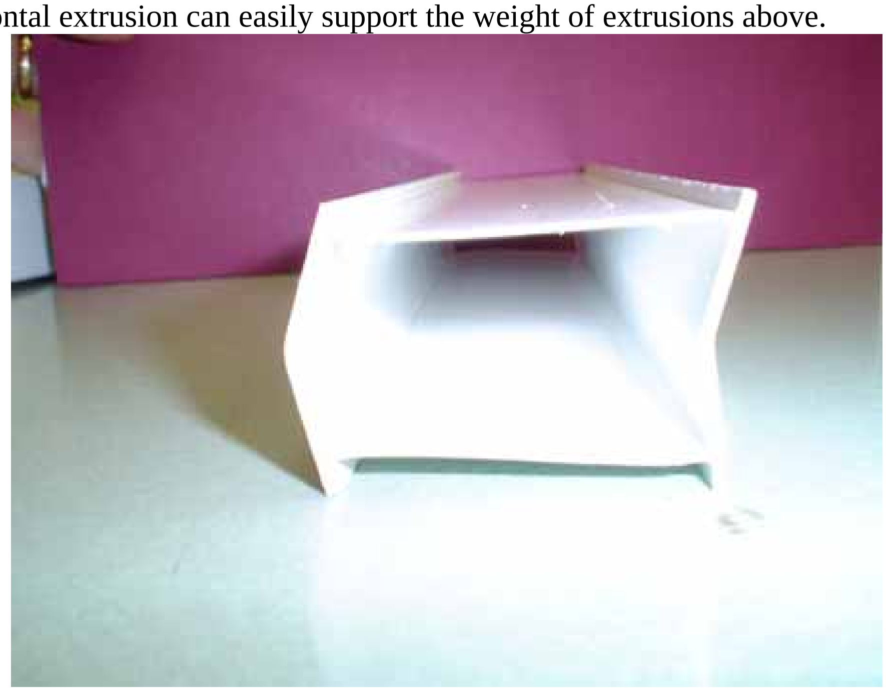

Figure 6. Buckled Side wall Sample

A second buckle test was performed in which identical samples were compressed but turned 90 degrees so that the web was under compression. When under pressure the webs of the extrusions will be under tension, however, if a cell looses its liquid it would be subjected to compression from adjacent extrusions. In this situation the extrusion webs would be subjected to compression. Six samples were tested with an average load to buckle of 128.2 lbs and a standard deviation of 2.82 lbs. The extrusions are significantly weaker in this orientation because of the thinner wall of the interior web.

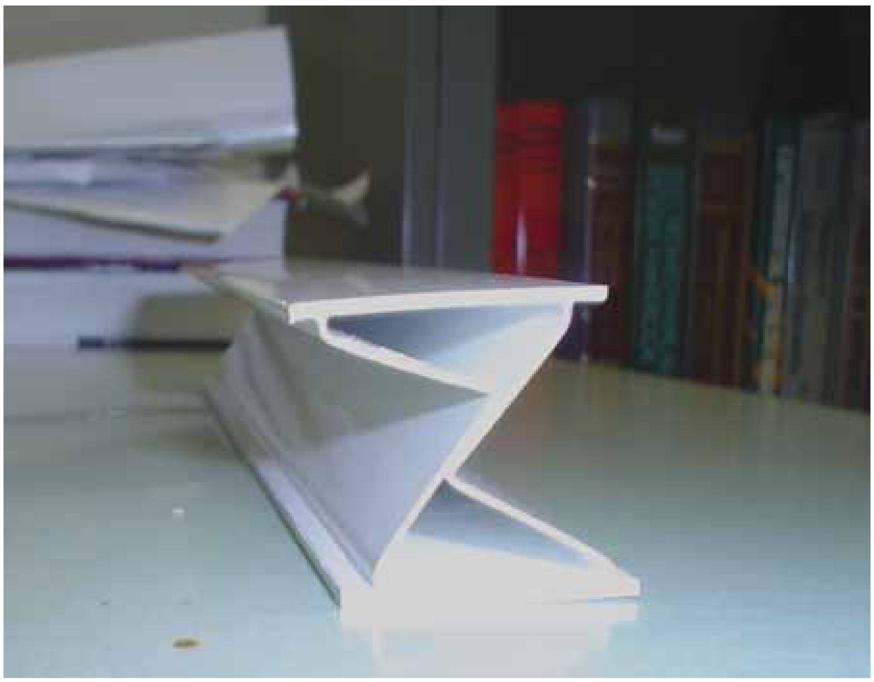

Figure 7. Buckled Specimen

The FEA model to compare to these buckle experiments have not been conducted yet.

2.3. Pressure inside of Cell.

Several FEA models of PVC cells under pressure have been created. These all show a dependence upon whether the side wall is constrained. There are several loading scenarios that are a concern:

- Maximum allowable pressure in the vertical extrusions.
- How the weight of the upper horizontal extrusions is transferred to the bottom horizontal extrusion. Is the weight transferred through the side wall or through some combination of the sidewall and by increasing pressure on the top cell?
- What is the effect of a rib failure from manufacturing?
- What is the effect if there is a leak on one cell within an extrusion looses liquid but the others don't?

These questions will be addressed through the following tests.

First, in order to test the maximum pressure that an extrusion can withstand a commercial extrusion will have its ends seals, filled with water, and pressurized at ANL. The sides of the extrusions will be restrained to mimic the FEA model and the maximum pressure before leaking will be measured. In the vertical extrusions filled with 17.5m of liquid the bottom is subjected to 21 psi of pressure.

Second, a half scale 4 plane prototype is being constructed at ANL and will be used to test the load transfer from the upper horizontal extrusions to the bottom horizontal extrusion. It is planned to seal the ends of the extrusions and to fill them will liquid. A pressure transducer will be placed inside the bottom cells to measure how the pressure increases due to the weight of the upper horizontal extrusions. In addition, a similar test will be conducted using shortened lengths of the commercial extrusion.

Third, a commercial extrusion that is 4ft long will have a center rib cut out. The ends will be sealed and it will be pressurized to failure in order to see the effect of internal rib failure.

Fourth, a commercial extrusion that is 4ft long will have its ends sealed. However, it will be sealed in such a way that the 2 center cells are isolate from the others on the ends. The end cells will then be filled with liquid and pressurized while the two center cells will not pressurized. This will test the effect of a leak within a cell.

2.4. Future Work

The following tasks need to be performed in the near future on the commercial extrusions:

- Complete the FEA modeling of the buckling of individual cells and compare them to the test results.
- Perform additional pressure tests on commercial cell panels with the ends sealed and pressure applied.
- Measure the increase in pressure in the 4 plane prototype.
- Perform pressure tests with ribs removed.
- Perform pressure tests with center cells under no pressure and without liquid.

3. PVC Mechanical Properties.

There are many commercial references that list the mechanical properties of PVC. The first step is to gather as much data from industrial sources as possible and to summarize and compare it.

However, it is likely that TASD will be using a mixture of PVC that is not commonly used in industry because of the higher level of titanium dioxide that is desired. Therefore, it is prudent to carry out a systematic testing of PVC in order to understand how its properties vary with its composition. It is difficult to perform a series of experiments with different levels of titanium dioxide because only commercial products are available that have prescribed levels of titanium dioxide. The vendor that has supplied the commercial extrusions being used in tests at ANL has indicated a willingness to supply extruded sheets that have a range a TiO_2 as well as other components if needed. These samples will be used to do a systematic series of tests on the strength of the PVC and effect of TiO_2 and other components on strength. Also, FNAL is currently working with a vendor to produce 3 cell extrusions with 12.5% titanium dioxide. If possible, this vendor should be asked to produce a series of extrusions that have a range of titanium dioxide from 8% to 15%. In addition, if it is determined from the review of published data on PVC mechanical properties that there is another variable that plays a strong role in the strength of the extrusion then the vendor should also be asked to make various runs using different combinations of this additional variable. Test samples can then be cut from the extrusions and standard tensile and creep tests can be performed in order to make a systematic comparison. (See Nova note#49 by Hans Jostlein and Appendix 2) Tensile and creep tests should be conducted on test specimens cut from the commercial extrusions in order to use these as inputs into the FEA modeling and as a first step in gaining and understanding of the strength of the PVC.

All testing should be done to standard testing methods such as the following ASTM standards:

D6436-02 Standard Guide for Reporting Properties for Plastics and Thermoplastic Elastomers

D6112-97 Standard Test Methods for Compressive and Flexural Creep and Creep-Rupture of Plastic Lumber and Shapes

D1784-03 Standard Specification for Rigid PVC Compounds

D882-02 Standard Test Method for Tensile Properties of Thin Plastic Sheeting

D695-02a Standard Test Method for Compressive Properties of Rigid Plastics

D638-03 Standard Test Method for Tensile Properties of Plastics

3.1. Future Work

The following tasks need to be completed in the near future:

- Perform a literature search and summarize the published data on PVC material properties and creep. (see for example Engineering Properties of Thermoplastics Ed. By R.M. Ogorkiewicz, Wiley Press, 1970, creep graphs in Appendix 3)
- Obtain PVC sample material with different levels of TiO_2
- Perform tensile tests
- Perform long term creep tests
- Define an acceptable working stress based on the tests described above. This working stress will be used in all subsequent analysis of the extrusions and structure.

4. Epoxy Testing

There are two applications of epoxy in the TASD structure. The first use of epoxy is to attach the end plug and manifold. The second use is to bond adjacent planes of extrusions to each other. The requirements for each of these applications are not the same and different epoxies could be used.

4.1. End-Plug and Manifold Epoxy

The requirements for the End-Plug and Manifold Epoxy are the following:

- Compatibility with scintillator
- Ease of Application
- A long cure time is acceptable
- Low cost
- Long pot life

UMN and ANL have investigated several epoxies already which include standard PVC cement, 3M 810 epoxy, and Araldite 2001. PVC manufacturers have also recommended for testing ResinLab EP1056 LV. In order to evaluate these epoxies standard shear and tensile test should be conducted according to the following ASTM standards:

D6465-99 Standard Guide for Selecting Aerospace and General Purpose Adhesives and Sealants

D4896-01 Standard Guide for Use of Adhesive Bonded Single Lap-Joint Specimen Test Results

D3164-03 Standard Test Method for Strength Properties of Adhesively Bonded Plastic Lap-Shear Sandwich Joints in Shear by Tension Loading

D3163-01 Standard Test Method of Determining Strength of Adhesively Bonded Rigid Plastic Lap-Shear Joints in Shear by Tension Loading

D1144-99 Standard Practice for Determining Strength Development of Adhesive Bonds

It is important to follow these standards in order to be able to compare the results with manufacturer's data which has been developed using them.

Compatibility of the epoxy with the liquid scintillator is also very important. UMN engineering students (Nova note #46) have already done tests which have shown the PVC cement is compatible with liquid scintillator. Further tests should be conducted using the same methodology as the UMN tests to confirm this.

4.1.1. Testing of Joints Using Extrusions

The design of the endplugs and comparisons between the performances of various epoxies can also be done using the commercial extrusions. Prototypes of different bottom plug designs can be made and bonded into the commercial extrusion using different epoxies. By pressurizing these test specimens it is possible to get a relative comparison between the performances of the epoxy as well as to gain insight into the design of the bottom plug.

A simple test piece using a single cell is shown in Figure 8. An eight inch long cell cut from a full extrusion has its ends plugged with a piece of PVC machined to fit tightly into the cell. Several test specimens were made with the plug bonded in using different epoxies. The cells were then pressurized until a leak occurred. The results are summarized in the table below.

	# of Samples	Failure Pressure (psi)	Standard Dev.
PVC Cement	5	44.0	29.2
3M 810	5	34.0	4.1
Araldite	5	12.0	4.4
EP1056-LV	5	10	0
EP1056-LC	5	13.0	2.0

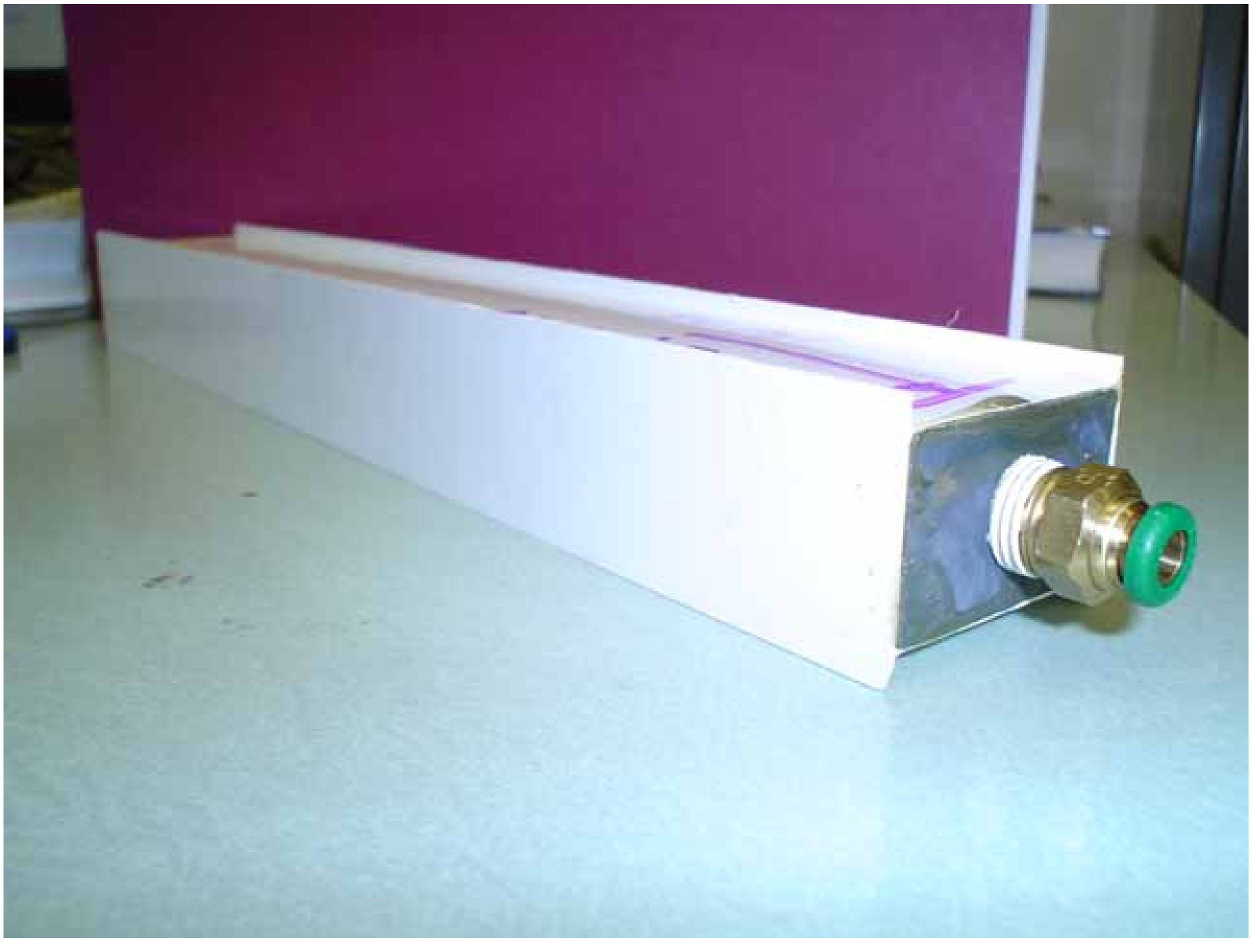

Figure 8. Epoxy Test Sample

4.2. Extrusion Bonding

The TASD structure will be constructed by bonding together alternating layers of horizontal and vertical extrusions. The requirements for the epoxy used for this bonding is the following:

- High strength
- Short cure time
- Low VOC
- Long pot life

A calculation has been done to put a scale on the strength that is needed for this epoxy (see Appendix 1). Assuming 100% coverage of the epoxy a tensile strength of 1.33 psi and a shear stress of 35 psi is required. The coverage of the epoxy can be reduced considerable and still have the required strength of the epoxy within acceptable limits.

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4.3. Future Work

The following tasks need to be completed in the near future:

- Based on tests at UMN and ANL 2-3 epoxies should be selected for future testing.
- Tests on mechanical strength should be conducted according to ASTM standards
- Tests on compatibility of epoxy with scintillator will be conducted.
- Tests on small samples of commercial extrusions will be done.

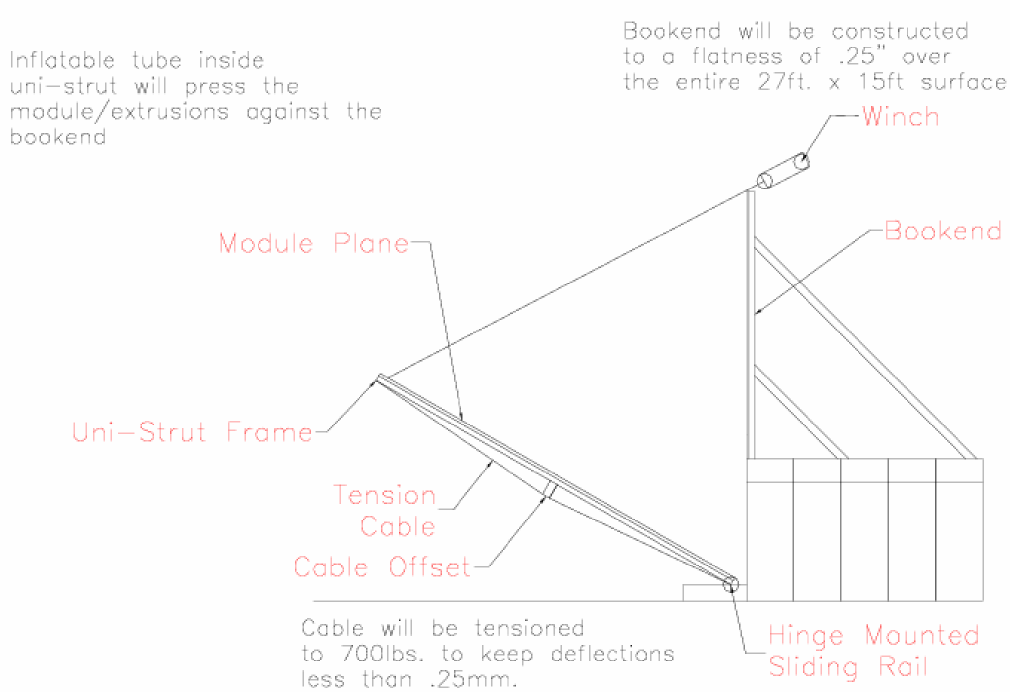
5. “Half Scale” 4 Plane Prototype

A cheap and easy way to answer many of the mechanical construction issues described above is to construct a large mechanical prototype using off-the-shelf commercial extrusions. At 27ft the mechanical prototype will be almost half size of the proposed detector. The prototype will contain 4 layers to verify predictions about the mechanical behavior of very long structures. The purposes of this prototype will be the following:

- Evaluate the flatness of large extrusions and how this affects the assembly.
- Evaluate the minimum amount of epoxy needed for structural strength and to eliminate bowing of the extrusion.

- Evaluate methods for assembling the detector. The initial plan calls for assembling an entire "plane" of a horizontal and vertical layers of extrusions.
- The extrusions will be filled with water and pressurized to evaluate deflections of an assembled structure.
- A temperature differential will be applied by placing heaters at the top or bottom of the prototype to evaluate the effect of thermal expansions.
- An FEA model will be made of the structure and a combination of strain gages and dial indicators will be used to measure deflections and stresses.
- The extrusions will be filled in different sequences to evaluate how this affects the structure.

The 4-layer PVC extrusion structure must be constrained to be vertical, flat and mechanically stable. This will be accomplished by attaching it to a 27ft high by 15ft wide vertical bookend structure. The bookend structure and method for lifting a plane of extrusions into place is shown in the figure below.



6. Design and Analysis of TASD Structure and Extrusions

The information and knowledge gained from the tests above will be used as input into the design of the TASD structure and extrusions. A series of analysis and physical testing needs to be done in order to develop the final design.

6.1. Extrusion Design

To date preliminary analysis has been conducted on the shape of the extrusions. The acceptable level of stress in the extrusions will be determined through the physical testing described above. Once this is determined the final geometry of the extrusion can be designed using FEA analysis. This analysis would then be confirmed through physical testing after prototype extrusions have been fabricated.

The calculations using the information available to date are summarized below.

Analysis of Vertical Cell

As an earlier study indicated, the stress at the vertical cell is about 5,300 psi for 2 mm wall. Compared with a recent inquired material RPVC 7181 from Georgia Gulf, the safety factor against yield is SF=Sy/Smax=1.15. The minimum SF is required to be 1.5, which is equivalent to use 2/3 of the yield stress as its allowable.

With an updated geometry, a 90-degree corner has been modified to a 3 mm chamfer or 1/8" radius fillet as shown in Figure 9. The Ansys shows that the stress has been improved from 5,300 psi to 3,900 psi for both 3 mm chamfer design and 1/8" radius fillet designs as shown in Figure 9. The difference between the 3 mm chamfer and 1/8" radius is negligible.

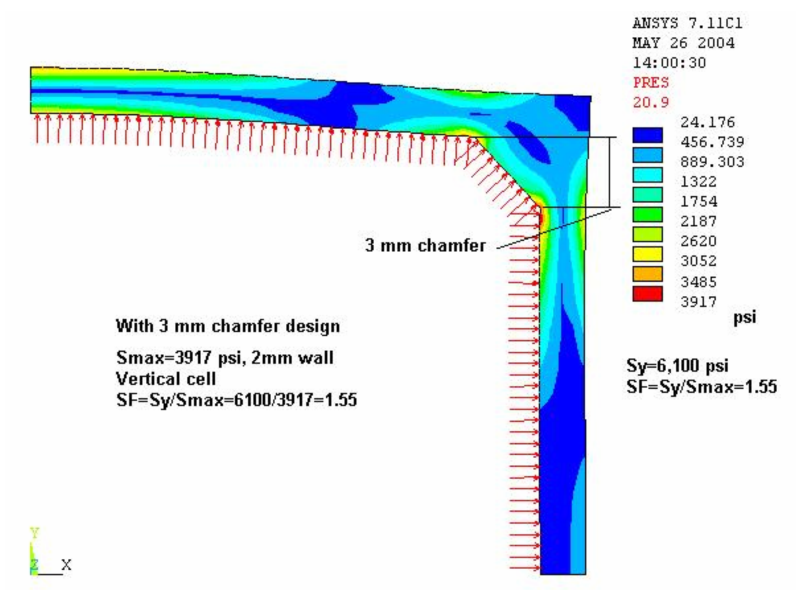


Figure 9 (a). The stress resultant for the vertical cell with 3 mm chamfer

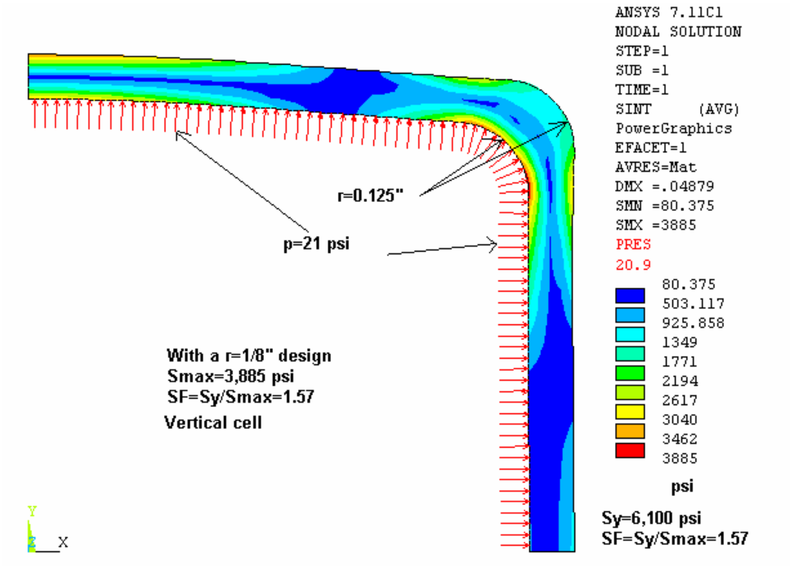


Figure 9 (b). The stress resultant for the vertical cell with 1/8" radius fillet

Analysis of Horizontal Cell

Since the horizontal cell is loaded with both a hydrostatic load within its own module and the gravitation load from top modules as a compressive force, two calculations have been done. One is to check its stability against the lowest cell buckling, and second one is to calculate the working stress against the material yield. The buckling calculation has been done with an assumption that the cell has 1.5 psi hydrostatic pressure around with a compressive force from top structure as a 22.3 lb/in, which is calculated as

1000 kg/module * 14modules* 2.2/(689"*2 sides)=22.3 lbf/in

This is probably a worst scenario. The eigenvalue solution from ANSYS shows a safety factor of 3.3 against the buckling as shown in Figure 10. This approach servers as a quick assessment only as stated in reference 2. As a further improvement, a non-linear large deflection analysis is carried out by increasing the load up to a point where the structure starts losing its load carrying capacity. The load verse displacement curve in Figure 11 reveals that the cell is very stable up 57 lbf/in. Then, it starts to curve up to 68 lbf/in. Any small load increased beyond that point would cause a very large or infinite displacement. If we used a 64 (lbf/in) as an average value for Pcr, SF will be 64/22.35=2.9. It is about 90% of SF= 3.3, calculated by eigenvalue method. Therefore, we do have some confidence about its stability calculation. A closed form solution has also indicated the SF being more than 3.

The stress calculation for the horizontal cell shows that the maximum stress is less 700 psi under the operating condition.

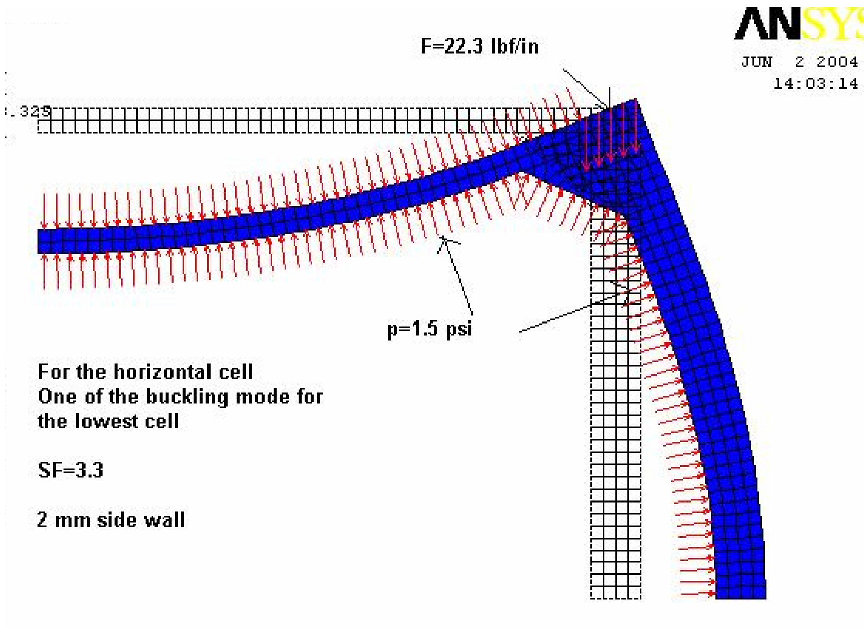


Figure 10. The buckling calculation based on eigenvalue approach

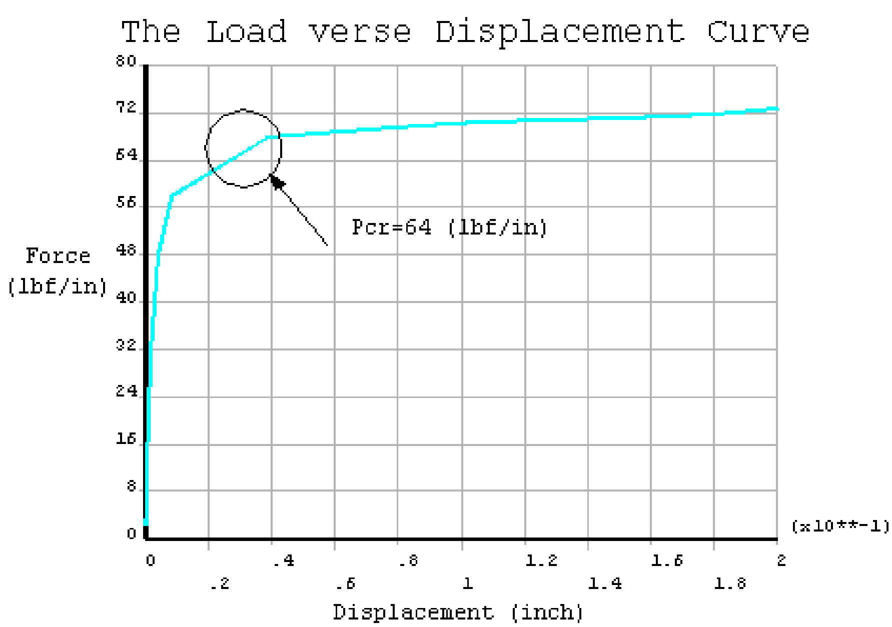


Figure 11. The buckling study based on a non-linear analysis

6.2. TASD Structure

The performance of the assembled TASD structure will also have to be analyzed in detail. Appendix 1 described a crude analysis of the forces on the epoxy between extrusions. Additional work that has already been carried out is described below.

The structure of the liquid scintillator is to have a horizontal plane and vertical plane alternated each other as shown in Figure 12. As a possibility, these two planes could be glued together. it is very interested to know how much strength it will carry. As an earlier study indicated, the maximum stress for the vertical cell is about 3,300 psi if it stays as a single plane. It is very close to its limit in terms of the safety factor. With a creep curve becomes available later, SF will be certainly brought down more or below to 1.5. Therefore, it may be desirable to look at so called “a combined strength” of the structure. By assuming they are glued together without any slippage as shown in Figure 12. The initial calculation shows that the divider in horizontal cell will be buckled first before the sidewall. We’ve understood that mode is probably impossible due to the fact that the vertical cell divider is indeed in tension while the horizontal divider is in compression. Having one side is in tension while the other side is in compression; the buckling chance for the divider is none as long as the tension side stress does not exceed its yield. The calculation shows the maximum tensile stress for the vertical divider is about 800 psi, which is well below to its yield. As a result, a simplified calculation is done by eliminating the divider for both vertical and horizontal cell. The statement is made that what safety factor SF will be for the buckling and working stress for a 4 mm wall. The Ansys calculation shows that the safety factor SF is more than 20 against the buckling and SF=6 against the yield for its working stress as shown in Figure 13 through Figure 15. Two planes gluing together does offer: (a) to increase the buckling capability (b) to reduce the working stress.

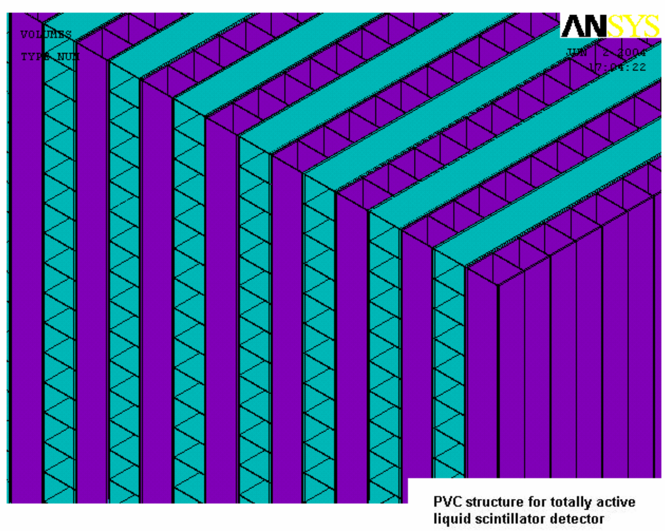


Figure 12 The proposed PVC structure [4]

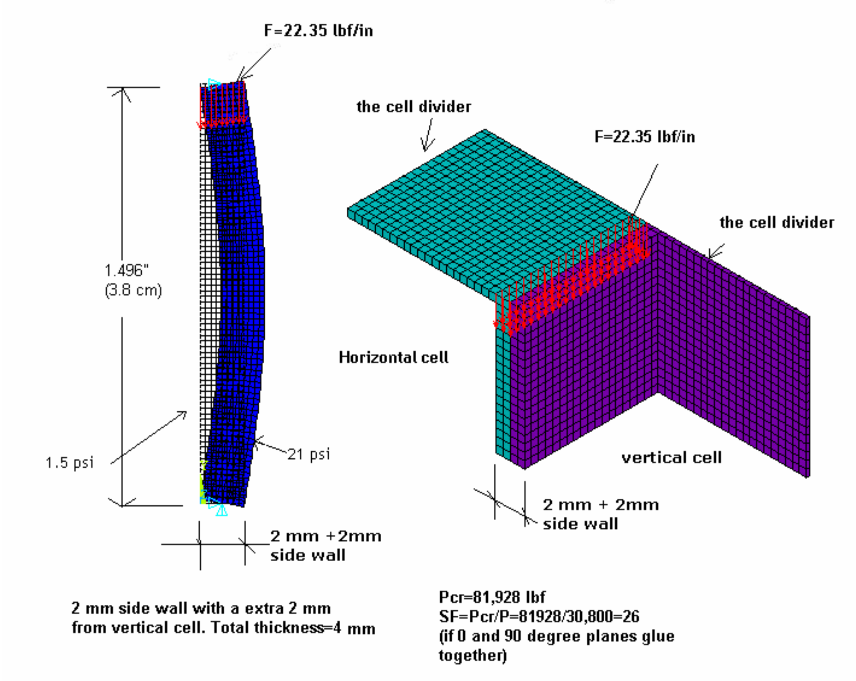


Figure 13. The Case for the gluing two planes (vertical and horizontal)

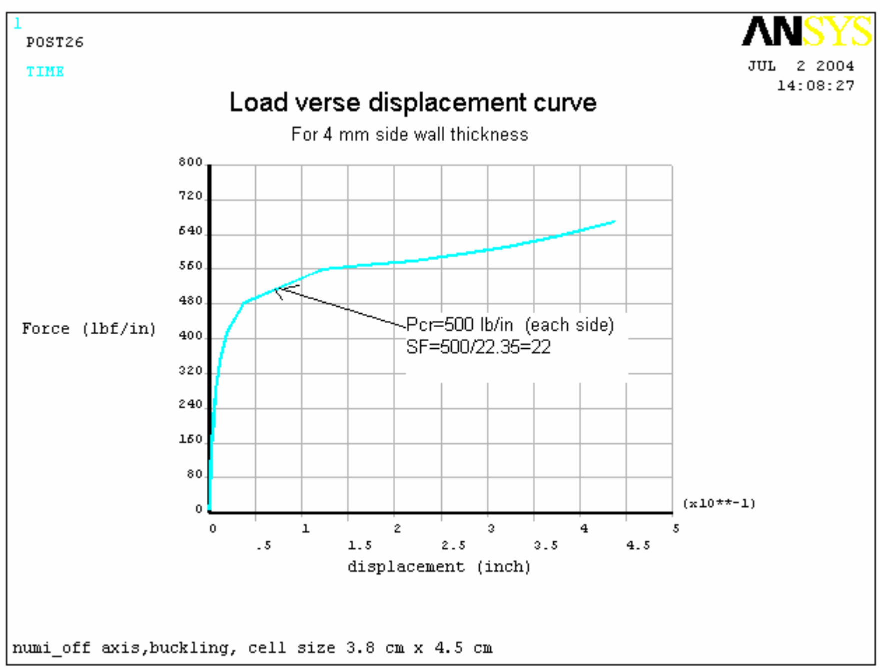


Figure 14. The collapsing force Pcr based on the non-linear Analysis for a 4 mm sidewall

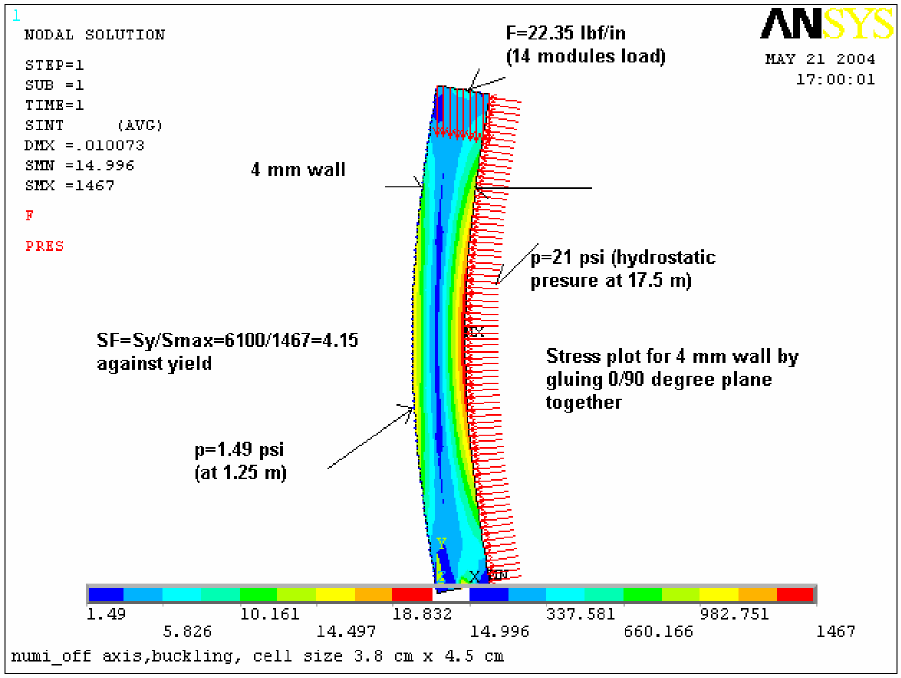


Figure 15. The working stress for the case of gluing 0/90 degree planes together

6.3. Future Analysis on TASD structure

After the tests and analysis described in sections 2.0 - 4.0 above have been concluded this knowledge gained will be used to inform final design and analysis of the structure. Future analyses that will be conducted are the following:

- Perform all required FEA analysis to mimic the tests currently being conducted on the commercial extrusion.
- FEA modeling of the proposed TASD extrusion geometry that reflects past analysis as well as knowledge gained from PVC testing and physical testing of the commercial extrusions.
- FEA modeling of the 4 plane mechanical prototype being constructed at ANL.
- Detailed FEA analysis of TASD assembled structure.
- When prototype extrusions of the TASD extrusion geometry have been produced physical testing and FEA modeling of physical testing on cell samples similar to the tests conducted on the commercial extrusion.

7. Conclusion

This paper has outlined a test plan for the extrusions and epoxy that will be used in the TASD design. This design will be using an epoxied/PVC extrusion structure with no other standard engineering materials being used for a support structure. As a result, extensive testing is needed in order to evaluate the performance of the PVC extrusions, epoxy, and to confirm the method of analysis. The following tasks will occur in the near future:

Commercial Extrusion Tests

- Complete the FEA modeling of the buckling of individual cells and compare them to the test results.
- Perform additional pressure tests on commercial cell panels with the ends sealed and pressure applied.
- Measure the increase in pressure in the 4 plane prototype.
- Perform pressure tests with ribs removed.
- Perform pressure tests with center cells under no pressure and without liquid.

PVC Testing

- Perform a literature search and summarize the published data on PVC material properties and creep. (see for example Engineering Properties of Thermoplastics Ed. By R.M. Ogorkiewicz, Wiley Press, 1970, creep graphs in Appendix 3)
- Obtain PVC sample material with different levels of TiO2
- Perform tensile tests
- Perform long term creep tests
- Define an acceptable working stress based on the tests described above. This working stress will be used in all subsequent analysis of the extrusions and structure.

Glue Testing

- Based on tests at UMN and ANL 2-3 epoxies should be selected for future testing.
- Tests on mechanical strength should be conducted according to ASTM standards
- Tests on compatibility of epoxy with scintillator will be conducted.
- Tests on small samples of commercial extrusions will be done.

“Half Scale” 4 plane Prototype

- Complete bookend and strongback for lifting planes
- Assemble planes
- Perform tests and compare results to calculations
- Evaluate method for extrusion handling and assembling

Extrusion/Structure Design and Analysis

- FEA modeling of the proposed TASD extrusion geometry that reflects past analysis as well as knowledge gained from PVC testing and physical testing of the commercial extrusions.
- Detailed FEA analysis of TASD assembled structure.
- When prototype extrusions of the TASD extrusion geometry have been produced physical testing and FEA modeling of physical testing on cell samples similar to the tests conducted on the commercial extrusion.

Appendix 1

Estimation of Glue Force Between Extruded Layers in TASD Design

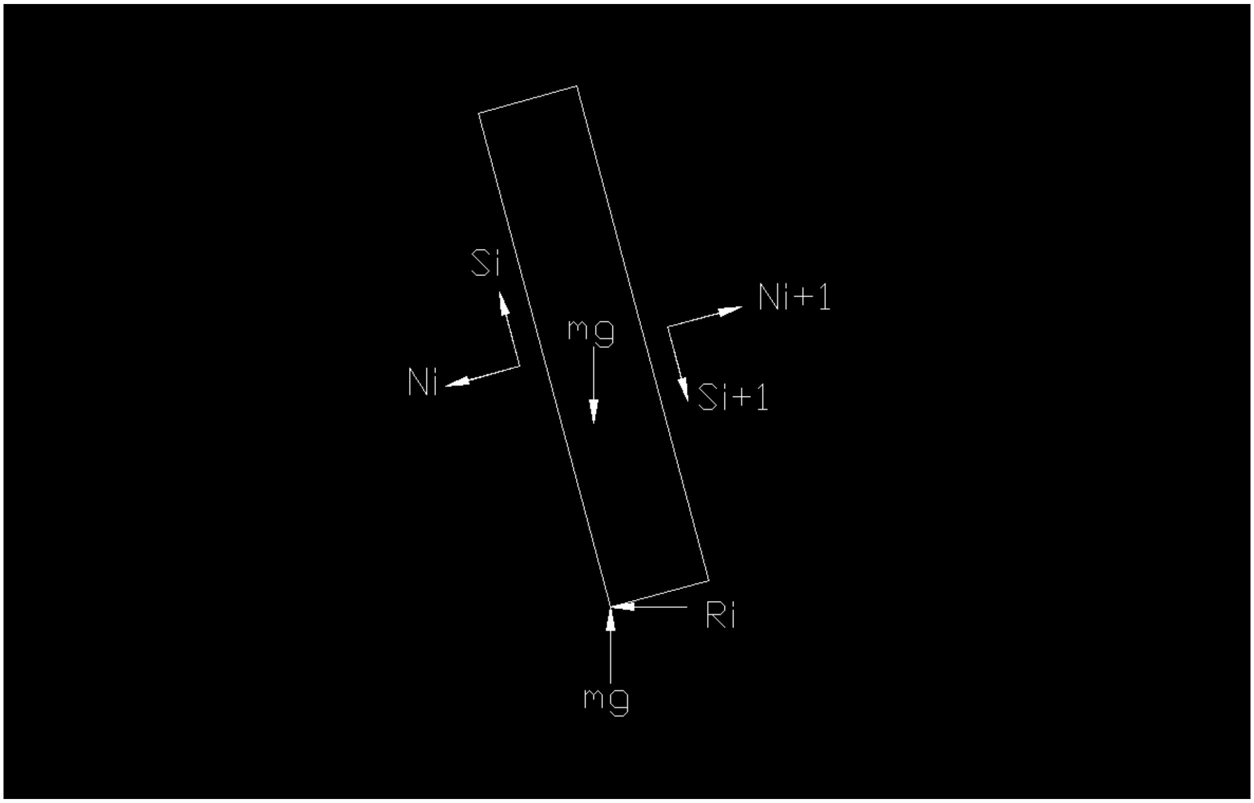
July 15, 2004

Victor Guarino

Introduction
A rough estimate is needed of the forces acting between extrusions in the TASD so that the amount and strength of the require glue joint (and possibly welded joint) can be determined. It is virtually impossible to calculate exactly what the glue forces will be because of uncertainties with the assembly, how well the extrusions will contact each other and transfer load, etc. However, it is possible to do a series of calculations in order to bound the problem and find extremes in the forces on the epoxy. In one extreme case all of the planes of extrusions are perfectly vertically. In this case the loads on the epoxy are minimal because all of the weight is transferred directly into the floor support. There are, however, several scenarios where the geometry is not ideal and results in additional loads on the epoxy. This paper will address several of these scenarios. The forces acting on one extrusion will be calculated.

Forces Due to Detector "Lean"
During the construction of the detector the planes will not remain vertical but instead will be at some angle. In a worst case situation the first plane against the strong back will be vertical but then every plane after that will begin to incline at some angle. For example, if there is a 1mm difference between the top and bottom of the detector (17.5m) then after 400 layers there will be a 400mm difference between the top and bottom of the detector which is an angle of 1.309 degrees. This skew of the detector results in increased loads on the epoxy. A simplified estimate of these forces was made by doing a simple static analysis.

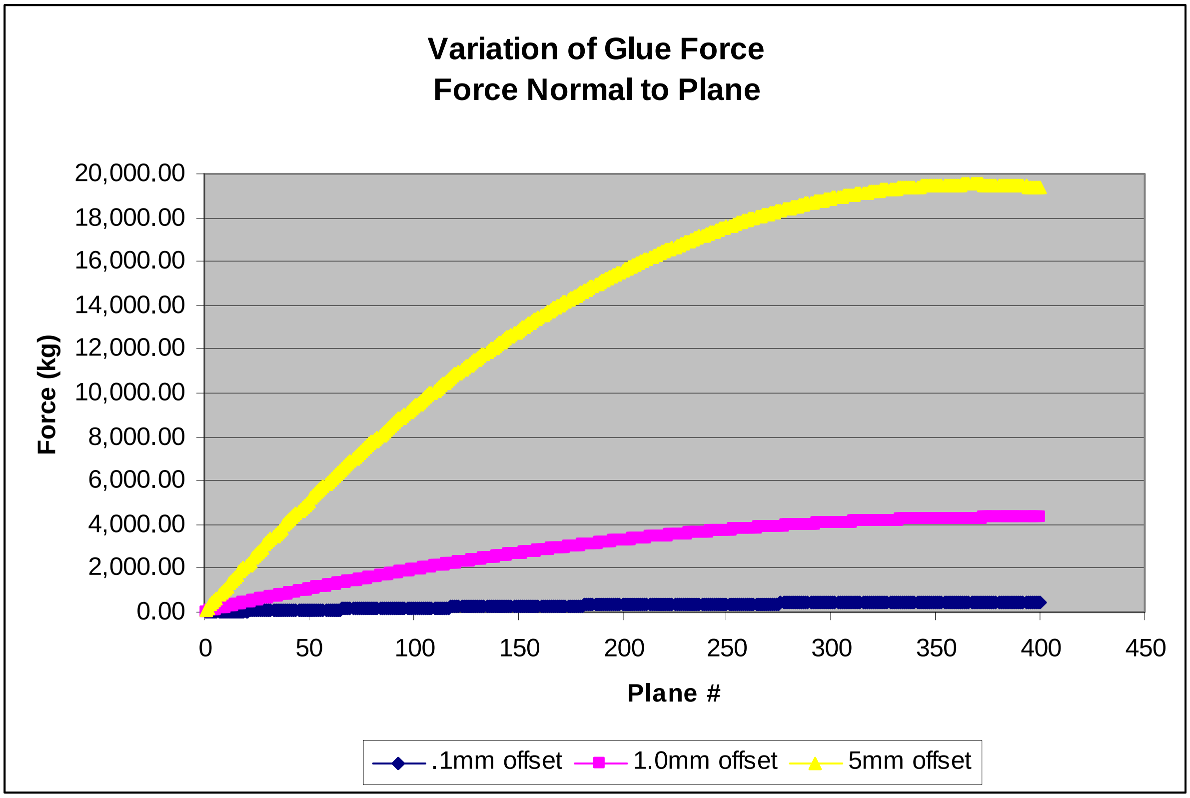
The figure below shows a single extrusion with the forces that are acting on it. The extrusion is shown at an exaggerated angle. On the side surfaces there is the shear force in the glue (S) and the normal force on the face of the extrusions (N). The weight and shear reaction (R) at the bottom of the extrusion are also shown. It is assumed that the angle is small so the vertical reaction at the bottom of the extrusion is equal to the weight. There is also a shear force, R, shown at the bottom of the extrusion. The forces on each extrusion can be found by solving the system of linear equations that result from this simplified model.

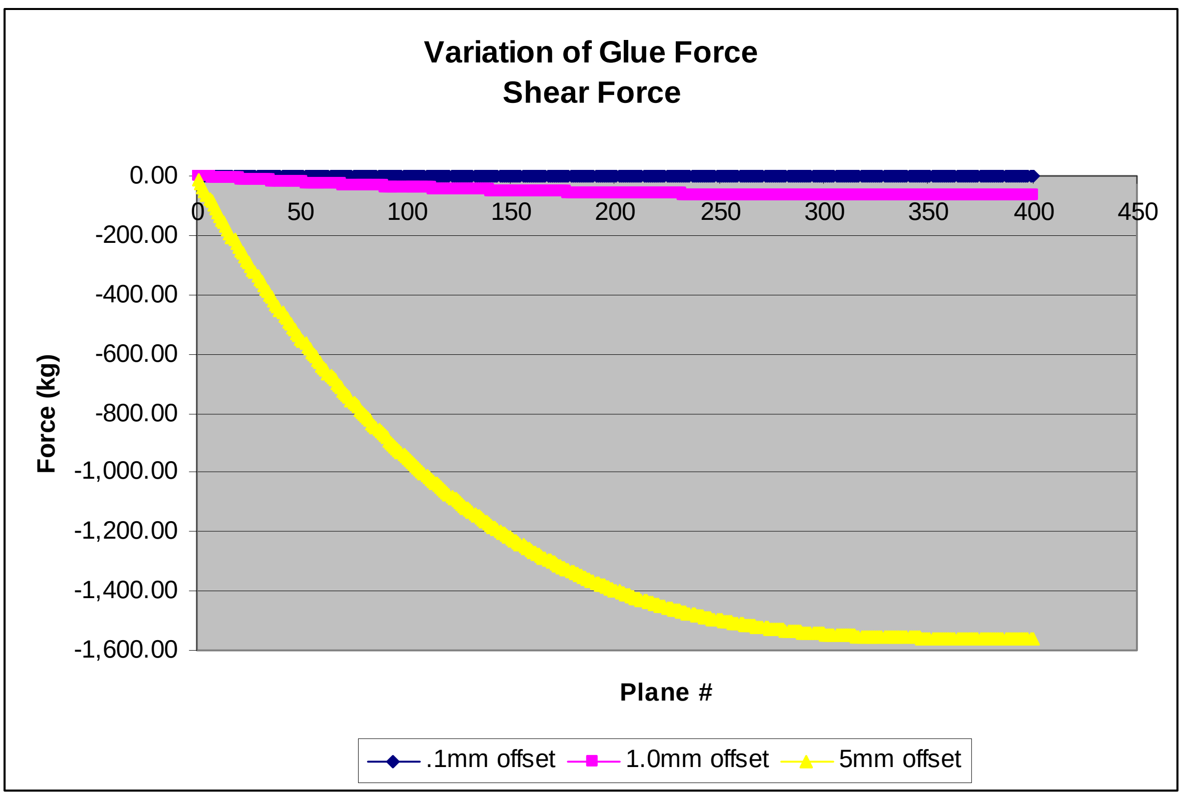


The forces were calculated for an extrusion that is 1283mm wide, 17500mm long (high) and 49mm thick. This problem is linear with the width of the detector so the forces acting on a plate is simply the forces calculated here for one extrusion multiplied by the number of extrusions that make up a plane. It was assumed that there were 400 layers which is approximately 20m and is probably the longest we would be able to go without a book-end. The glue forces were calculated for systematic offsets between the top and bottom of an extrusion of .1mm, 1.0mm and 5mm. The results for the normal and shear glue forces on each extrusion are shown in the graphs below. (the extrusions are numbered so that #400 is against the bookend and #1 is unsupported and at the extreme angle.) The weight of an extrusion is 968kg.

The maximum normal force on the glue is at the book end and is nearly 20,000kg (20 tons) per extrusion. However, distributed over the large area of the extrusion that result in a normal stress on the glue of only .01MPa which is insignificant. The shear force is negligible (negative sign is just a result of the sign convention used). This analysis shows that the extrusions will have to be secured to the strongback and not simply leaning against it.

This rough calculation of the epoxy forces can provide some insight into the percent coverage that is needed with any epoxy.

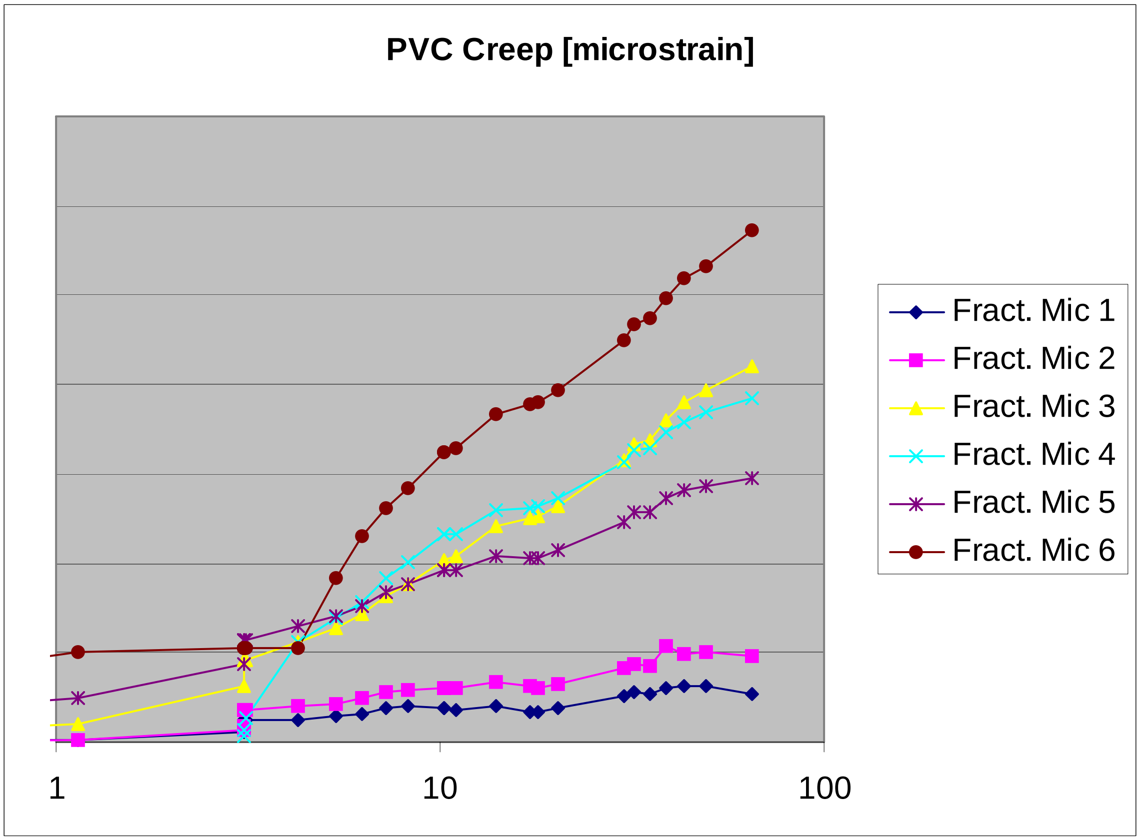

Variation of Glue Force
Force Normal to Plane
Force (kg)
20,000.00
18,000.00
16,000.00
14,000.00
12,000.00
10,000.00
8,000.00
6,000.00
4,000.00
2,000.00
0.00
0
50
100
150
200
250
300
350
400
450
Plane #
.1mm offset
1.0mm offset
5mm offset


Variation of Glue Force
Shear Force
Force (kg)
0.00
-200.00
-400.00
-600.00
-800.00
-1,000.00
-1,200.00
-1,400.00
-1,600.00
0
50
100
150
200
250
300
350
400
450
Plane #
.1mm offset
1.0mm offset
5mm offset

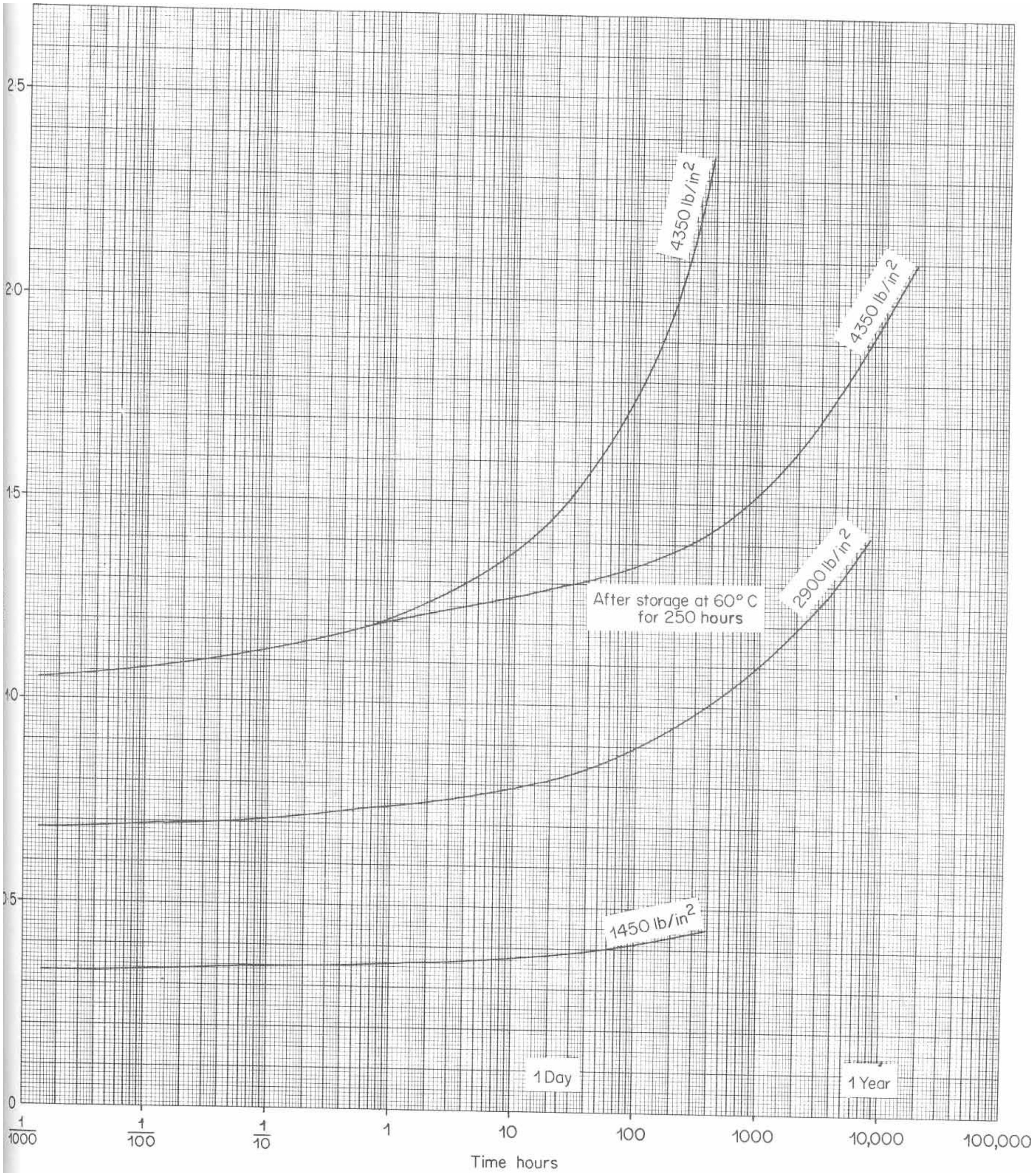
Offset between Horizontal Extrusions

A second scenario that can be calculated to bound the forces on the epoxy is for the horizontal extrusions. In the unlikely scenario that the bottom horizontal extrusion is placed so that it does not make contact with the bottom support structure of the detector and has to support the entire weight of the extrusions above it. If there are 12 extrusions per plane then the total shear force on this bottom extrusion is 11,616kg (11.6tons). If this load is distributed evenly over the surface of the extrusion the shear stress will be 5.1kPa (~35psi) which is insignificant.

Appendix 2
FNAL Creep Tests



Appendix 3
PVC Mechanical Data
<u>Engineering Properties of Thermoplastics</u> Ed. By R.M. Ogorkiewicz, Wiley Press, 1970



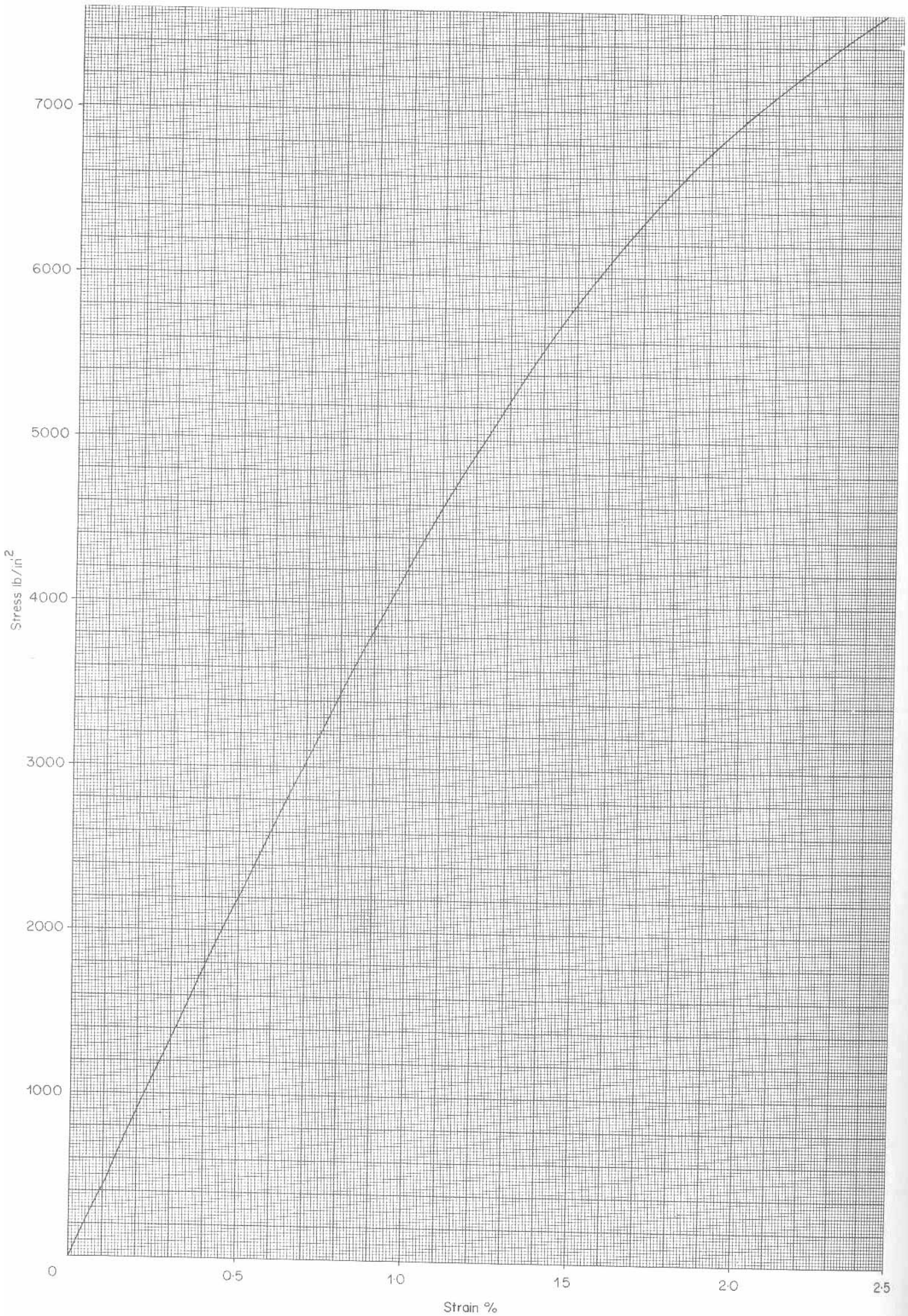


Figure 13.2. Isochronous stress vs strain curve: 20°C, 100 sec. Unplasticized PVC ('Darvic' 110)

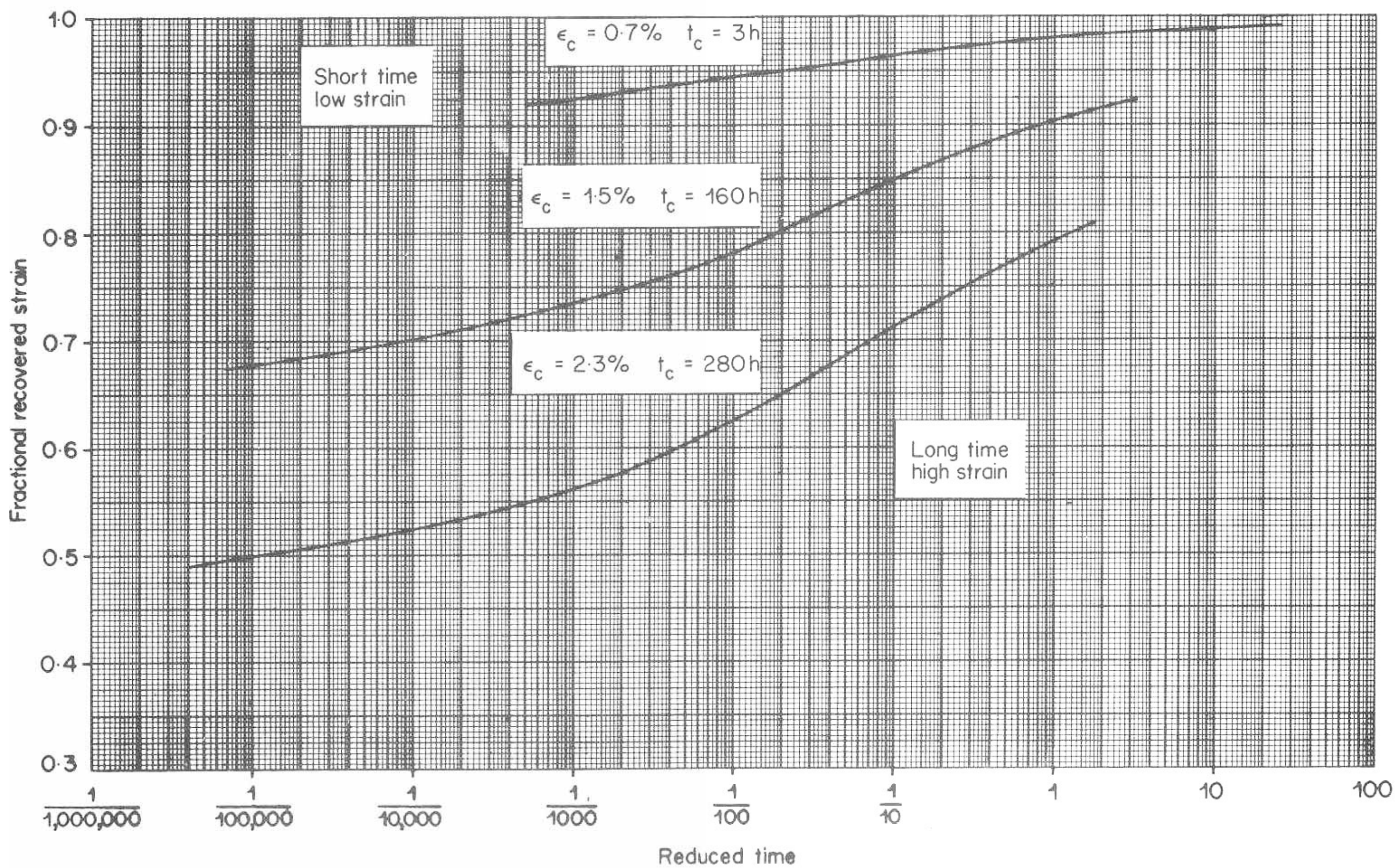


Figure 13.3. Recovery from creep in tension: 20°C. Unplasticized PVC ('Darvic' 110)

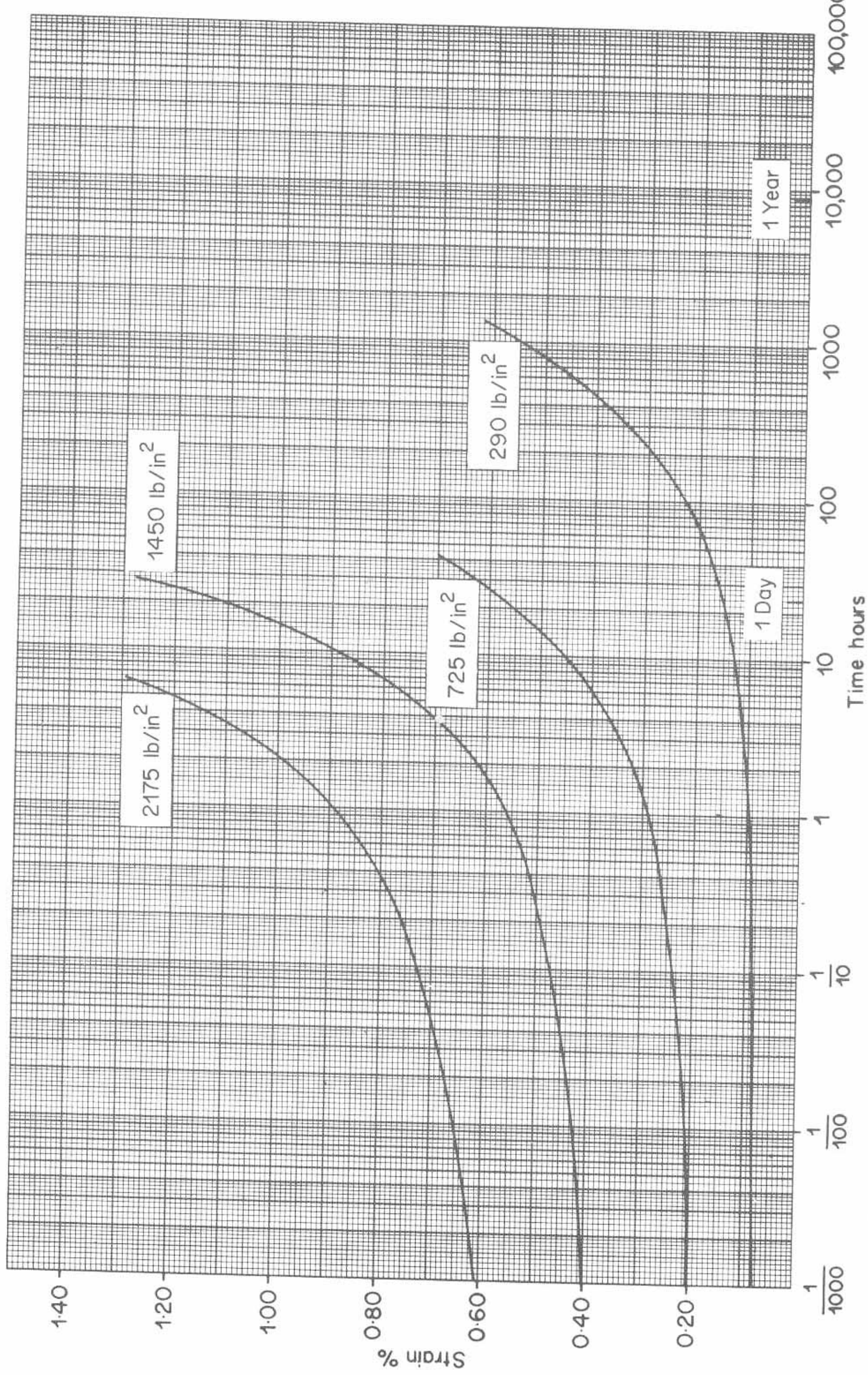


Figure 13.4. Creep curves in tension: 60°C. Unplasticized PVC ('Darvic' 110)